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SIMULATION OF METALLURGICAL PROCESSES

J. BOWKER
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ABSTRACT

A review of the simulation of the weld heat affected zone, continuous casting and hot rolling is presented. The use of the Gleeble, a thermal/mechanical simulator, in the development of the simulation of these metallurgical processes is discussed and shown in the case of the weld heat affected to have been of great benefit in improving the toughness of this region in pipeline steels. The potential for using the Gleeble in the examination of cracking during continuous casting is shown to be great.

Minerals Research Laboratories, Physical Metallurgy Research Laboratories, CANMET, Energy, Mines & Resources Canada, Ottawa

LABORATOIRES DE RECHERCHE SUR LA MÉTALLURGIE PHYSIQUE
RAPPORT MRP/PMRL 83-24(TR)

SIMULATION DE PROCÉDÉS MÉTALLURGIQUES

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RÉSUMÉ

L'auteur a utilisé le simulateur thermo-mécanique gleeble pour étudier les phénomènes rencontrés lors de la coulée en continu, du laminage à chaud et dans les zones affectées par la chaleur lors du soudage. On discute de l'utilisation de cet appareil lors de l'étude de ces phénomènes. On montre aussi combien il a été grandement avantageux de se servir du simulateur dans l'étude des zones affectées par la chaleur lors du soudage parce qu'il a ainsi été possible d'améliorer la résistance de cette région dans les aciers utilisés pour les pipe-lines. Il semble qu'il sera aussi très avantageux d'utiliser le simulateur pour étudier les problèmes de fissuration en coulée continue.

Laboratoires de recherche sur les minéraux, Laboratoires de recherche sur la métallurgie physique, Énergie, Mines et Ressources Canada, Ottawa

INTRODUCTION

Since the development of thermal simulators, the first effective one being the Gleeble, a considerable amount of interest has been directed towards the simulation of metallurgical processes. Until recently this has mainly involved study of the weld heat affected zone, however, the simulation of processes such as continuous casting and hot rolling are now receiving more attention.

In welding the thermal simulator is able to reproduce the weld thermal history of the heat affected zone (HAZ) under well defined conditions in specimens which are large enough for the evaluation of mechanical properties and microstructure. In addition when the thermal simulator is used in conjunction with a high speed dilatometer the transformation characteristics of the material to be welded can be determined. It is then possible to make use of these results when selecting a material and welding procedure for a given application.

The cracking of steels during continuous casting has long been recognized as a problem. It is only over the past 10 years however that attempts have been made to simulate the thermal history of continuous cast slabs and examine the changes in strength and ductility which take place over the temperature range of interest, i.e., melting point to 600°C. This knowledge is leading to an improved understanding of crack mechanisms and is helping to explain the known operating causes of crack formation in microalloy steels. More information on compositional effects, including effects of deoxidation practice is needed. A more detailed understanding of the underlying mechanisms controlling elevated temperature ductility needs to be developed in order that the findings in laboratory tests can be extended to actual castings.

The thermal history of hot-rolled plate or strip is complex. The cooling rate in the sprays is faster than air cooling and after coiling or piling the cooling rate is very slow (~1°C/min) approaching an isothermal treatment. In order to simulate mill conditions in the laboratory, it is necessary to duplicate the per cent reduction prior to final austenite recrystallisation in the finishing stand, the finishing temperature, the cooling rate of the strip on the runout table, the coil or pile temperature and the cooling rate in the coil. If the above process variables can be simulated then the potential for improvement in the properties of hot-rolled steel is great.

A review of the literature will be presented to indicate the extent to which these processes can realistically be simulated. This will be followed by a description of the Gleeble, one of the best known thermal/mechanical simulators, and the way it is currently being used at PMRL in a program to develop simulation procedures for the metallurgical processes previously mentioned.

REVIEW OF THE LITERATURE

SIMULATION OF THE WELD HEAT AFFECTED ZONE (HAZ)

During welding a region adjacent to the weld pool experiences a thermal heating/cooling cycle embracing a range of peak temperatures extending from the melting temperature to ambient plate temperature and thus all possible thermally activated processes must occur at some location near a weld. This produces a continuous gradation of microstructures each with its own chemical and mechanical properties. The determination of these properties from actual welds is made difficult by the rapidly changing microstructure which exists over a short distance adjacent to the fusion zone. Thus in order to study the properties characteristic of the individual microstructures within weld HAZ's, a zone of uniform microstructure which is large enough for the reliable determination of mechanical properties needs to be produced. For this reason suitable test specimens are given thermal treatments characteristic of particular points in the real HAZ using a thermal simulator (1), a device employing either induction or more commonly resistance heating.

To obtain weld thermal cycles there are two approaches available, the first involves the solutions of the heat flow equation in terms of relevant welding parameters, that were first introduced by Rosenthal. They give the temperature at a point lying a given distance from the weld line as a function of the time for a certain energy input. Two limiting solutions exist, one for very thick plates (3 dimensional heat flow) and the other for very thin plates (2 dimensional heat flow). Real welds usually lie within these extremes which limits the usefulness of this approach because of the difficulty in applying boundary conditions. It has been shown however, that accurate predictions can be made by a numerical solution of the equation using computer techniques (3,4).

The alternative approach is to measure experimentally the thermal cycles using suitably located thermocouples. This can be carried out simply

and yields results directly, so consequently much of the available data has been determined this way (1,5-7). An example of the typical thermal cycles obtained near an arc weld made with a 2.75 kJ/mm heat input in 12 mm steel plate is shown in Fig. 1. The thermal cycle is characterized by two parameters, i.e., the peak temperature and the cooling time between 800 and 500°C, which is essentially the same in all points of the weld and HAZ.

The peak temperature indicates whether austenitization has taken place and if so the extent of grain coarsening. The cooling rate will then indicate what transformation products are likely to form.

In order to be able to predict the microstructures in the HAZ of a weld with the aid of a thermal simulator, a comparison has to be made between the austenite grain size and type of microstructure formed during cooling in simulated and real weld conditions. This has been performed by several authors (9,10). Using direct resistance heating as a means of simulating thermal cycles in two steels Berkhout (9) showed that the grain size depended to a great extent on the peak temperature with fluctuations in heating and cooling rates having little effect. It was found for the region immediately next to the fusion line in a real weld where peak temperatures above approx. 1300°C were reached, that the grain size was finer than would be expected on the basis of the measurements of the simulated specimens. This difference was found to increase as the cooling time decreased, and was explained by the presence of the temperature gradient in the HAZ as follows. At a particular point in the HAZ above the Ac_3 isotherm, the growth of an austenite grain simultaneously takes place towards regions of lower peak temperature and towards regions of higher temperature. Growth towards lower temperature regions will be restricted because of the lower energy available, whilst growth towards higher temperature regions will be difficult because competitive growth with grains at higher temperatures.

In contrast, grain growth on the centreline of thermally simulated specimens occurs in a large (in relation to the grains themselves) volume of equal temperature until a temperature time equilibrium is reached.

Dolby (10) found a discrepancy in austenite grain size between the real weld HAZ and resistance heated simulated samples for two quenched and tempered low alloy steels. In order to overcome this discrepancy he needed to program a simulated peak temperature of 1210°C rather than 1340°C but with the heating and cooling rates appropriate to the peak temperature of 1340°C.

Dolby accounted for this difference in terms of the temperature gradient in the heat affected zone as described above, with the finite bead size of the thermocouples attached to the specimens also playing a part. It was shown that an error of ~30°C was produced when a beaded thermocouple was welded to the surface because the two thermocouple leads are connected by a current path that is remote from the point of attachment to the specimen. This error and means of remedying it will be discussed in the next section on the Gleeble, a thermal simulator.

Based on the experimental work already carried out it can be said that the thermal simulating technique offers a good method of predicting the weld HAZ microstructures. An evaluation of the toughness of a given region of the heat affected zone can be made by performing instrumented Charpy or COD tests on simulated samples. These results compare favourably with the same tests on the same region of the real HAZ.

It is evident that simulation of the weld HAZ can provide useful information on which to base changes in process variables for improved mechanical properties. There are many avenues, however, for further work on HAZ's. Some of these are as follows:

i) increased data on real vs simulated correlation including grain size and temperature correspondence in specimens using the Gleeble, a more sophisticated thermal simulator than those previously used to study this subject

ii) increased information on the effects of multicycling and postweld heat treatment, especially in the temper embrittlement range

iii) the relevance of simulation studies to the properties of HAZ's in real structures

SIMULATION OF CONTINUOUS CASTING

From the onset of solidification in the mould until well after solidification is complete, a continuously-cast section is subjected to a complex history of thermal and mechanical stresses. The thermal stresses arise from the rapid cooling of the slab in the mould while the mechanical stresses are caused by factors including friction in the mould, roll pressure, ferrostatic pressure, machine alignment and bending and straightening operations (12,13). In order for the casting process to proceed it is important that the cast section be able to withstand these stresses. When this is not the case the inevitable result is the formation of cracks either at the surface or inside

the slab. In the interior, cracks may be seen near the corners, at the centreline or diagonally between opposite corners. On the surface, transverse or longitudinal cracks may appear at both the midface and corner regions.

Reviews of the causes of, and solutions to these types of cracks (14-16) have tended to treat each type of crack as a separate problem, mainly from an operating standpoint. A scientific approach to the problem should relate the presence of cracks not only to operating stresses and strains but also to the mechanical properties of steel at continuous casting temperatures. However, the lack of reliable data for the calculation (without too many assumptions) of the stresses and strains that are likely to arise and the fact that there are no representative trial and test methods that can duplicate the multiaxial characteristics of these stresses makes the prediction of cracking rather difficult. A good indication of the susceptibility of a slab to cracking can be made by simulating the thermal history of the process and examining the hot ductility of the material over the temperature range of interest (12,13,17,18).

Previous studies of the simulation of continuous casting have involved the melting, solidification and hot tensile testing of samples in a thermal/mechanical simulator. The results (12,13,17) for steels that have received a thermal cycle typical of that given in Fig. 2 followed by tensile testing at different temperatures with a range of strain rates have shown that there are distinct temperature ranges in which the steel has low ductility and is therefore susceptible to cracking. The form of the ductility-temperature curve depends on the steel composition and strain rate. A ductility curve typical of a low carbon steel is shown in Fig. 3; the poor ductility close to the melting point is from liquid grain boundary embrittlement. This drop in ductility which does not depend on strain rate is thought to be responsible for most of the internal cracks. At lower temperatures (900-1100°C) another region of low ductility occurs as a result of intergranular precipitation of sulphides and oxides. The degree of embrittlement in this temperature range decreases as the Mn:S ratio of the steel increases and as the rate of deformation and cooling rate decreases. The significance of this low ductility zone to a specific cracking phenomenon in the cast product is not clear. Further work examining the ductility under thermal history conditions that relate directly to a given section of a cast slab needs to be performed.

A third zone of poor ductility exists for some steels including those containing Al and Nb (17,19). The cause of this embrittlement is thought to be the grain boundary precipitation of nitrides or carbonitrides depending on the composition of the steel.

Although considerable progress has been made in using the melting and solidification simulator procedure to investigate cracking problems in continuous casting, further work is necessary. The effects of changes in steel composition needs to be studied more fully under conditions that follow more closely those existing in the casting process.

SIMULATION OF HOT ROLLING

Hot rolling of steel is a high temperature thermo-mechanical process that generally consists of two stages. The first stage involves the deformation of austenite by a series of rolling passes in a temperature range where dynamic and static recrystallisation occur, with the aim of producing a fine recrystallised austenite grain size. The second stage consists of further rolling passes below the recrystallisation temperature to enhance the formation of fine ferrite grains following the final rolling pass and thus provide good strength and toughness.

The evolution of austenite structures during rolling depends on a number of operating parameters including the temperature to which the slab was reheated before rolling, the alloying elements present and the temperature reduction sequence. Figure 4 presents a diagram which shows the interrelationships of these and other factors involved in hot rolling.

Growing energy needs and the prospect of working with gas or petroleum deposits in severe environments, e.g., Alaska, has brought about new requirements in terms of minimum mechanical properties for pipeline steels. In order to develop rolling procedures to produce steels meeting these property requirements and to reduce the need for expensive plant trials there has been an increasing tendency for the use of universal testing systems to simulate hot rolling. Both high temperature strength and microstructure can be obtained from tension (20,21), compression (22,23) and torsion (24-28) tests and rolling loads and torques can be determined on laboratory mills (29). Each of the above methods has limitations; the tension test cannot tolerate large strains since necking occurs relatively early during straining; in a similar manner friction and barreling limit the amount of deformation

that can be imposed by compression. The torsion test, however, can produce large enough strains but has the disadvantage that the strain and the stress gradually increase from zero at the centre to a maximum at the surface of a twisted sample. Most previous work on rolling simulation has been carried out at constant temperature (24-26). In such work, each deformation cycle is applied at a different temperature, but with the same initial microstructure. More recently the torsion test has been applied over continuously decreasing temperatures with success in predicting rolling forces and simulating structures (28,30). Some success has also been achieved using the Gleeble thermal simulator in duplicating hot rolled structures (31); the deformation in this case however is tensile and at constant temperature. The usefulness of the Gleeble in simulating hot rolling is yet to be proven.

DESCRIPTION OF THE GLEEBLE (A THERMAL/MECHANICAL SIMULATOR)

The Gleeble is a system capable of following a wide range of preprogrammed thermal histories using resistance heating. The rate of heating is rapid (up to 8000°C/S) however the rate of cooling is limited by the rate at which heat can be extracted through the water cooled grips. Temperature control is provided by means of either a thermocouple or pyrometer. For reliable thermocouple control there should be good metallurgical contact with minimal heat loss through the wires. Excessive beading of the thermocouple should be avoided because the effective junction may be at an appreciably lower temperature than the specimen. It has been found that attaching wires individually gives more reproducible results and this procedure has now been adopted at PMRL (32). Using a pyrometer for temperature control requires calibration because the response of the pyrometer to temperature is non linear, i.e., the specimen emissivity is temperature dependent. Calibration is performed by setting the emissivity response of the pyrometer to a value at which its temperature agrees with that of a reliable thermocouple for a given elevated temperature, say 1350°C, then decreasing the actual temperature in stages whilst monitoring the pyrometer readings.

Tests are conducted in a protective environment, usually argon, to prevent oxidation of the sample. It is possible to use a range of sample geometry and size although round (10 mm diam) and square cross section (10 mm edge) are most common. To increase the cooling rate smaller samples may be

used with a reduced grip separation. If larger specimens are needed a maximum diameter or edge of 25 mm can be accommodated.

The Gleeble is capable of providing mechanical loading under tension or compression. It can be programmed under load control using feedback from a load cell, while stroke or dilation control are provided using feedback from either an extensometer or dilatometer.

The Gleeble is a versatile thermo-mechanical simulation device that has become an important instrument in research on metallurgical processes such as welding. It has been successful in providing an understanding of the formation of cracks in continuous casting of steel and is only now being applied to hot rolling.

DEVELOPMENT OF SIMULATION PROCEDURES USING THE GLEEBLE

THE WELD HEAT AFFECTED ZONE

A number of studies of the weld heat affected zone of pipeline steels have been performed at PMRL (7,33-36) with an aim to understanding the relationship between structure and properties in this region. The Gleeble has been used to simulate the thermal profiles appropriate to the various welding conditions and positions in the HAZ. In all these investigations the thermal profiles were obtained experimentally from welding operations and were reproduced exactly in the Gleeble under Pt-Pt 13% Rh thermocouple control. The toughness of the simulated samples was determined using COD, instrumented Charpy or Charpy V-notch tests and the microstructures examined optically. It was reported in one of the studies (36) that good agreement existed between the simulated and real-weld data and therefore laboratory studies could play an important part in trials on experimental steels for improved toughness.

More recently the simulation procedure at PMRL has made use of the pyrometer as a means of temperature control. This has required calibration of the instrument against a thermocouple over the temperature range 250 to 1350°C by setting the emissivity so that the pyrometer and thermocouple temperatures agreed at 1350°C. This has allowed fast, reliable and reproducible simulations to be carried out.

A systematic study of the difference between the austenite grain size of real and simulated weld HAZ's for a given peak temperature needs to be carried out. This will be achieved by measuring thermal profiles at various distances from the fusion line of a single bead weld, followed by a

simulation of these profiles and a comparison of structures. It is also important that the temperature distribution on a blank Charpy Gleeble sample be characterised for a given grip separation. This has been performed longitudinally along the middle of one face using a thermocouple, for a grip separation of 30 mm. The results that are shown in Fig. 5 indicate that the temperature is within ± 10°C over a distance of 5 mm at the centre of the sample which is wide enough for reliable evaluation of toughness using a suitable notch toughness test. More importantly however the temperature from centre to surface needs to be measured because any large difference will produce a gradation in microstructure which will affect any testing procedure carried out.

CONTINUOUS CASTING

A continuously-cast slab undergoes a complex thermal and mechanical cycle the nature of which is impossible to simulate on small scale samples. For example the thermal gradient present from surface to centre in the slab during cooling in the mould is of the order of 200°C. However it is possible to simulate the thermal history of a small section of the slab and determine its properties at various stages of the continuous-casting process. The properties need to be obtained at a strain rate relevant to commercial practice and although actual strain rates are not exactly known, a good estimate can usually be made.

A simulation procedure has been developed using the Gleeble to simulate continuous casting as part of a co-operative project with Stelco and Algoma. Stelco has sent samples cut from low carbon strip product at various positions in order to select the most representative region for sampling. Algoma has sent 11 sections of cast slabs of different compositions each from the same sampling location.

Preliminary tests to develop the best technique were carried out on round mild steel bar of the following composition:-

C	Mn	Si	S	P
0.24	0.49	0.16	0.007	0.005

Fused quartz was selected as the material to support the sample while it was molten. A slit was needed to allow thermal feedback from the sample using either thermocouple or pyrometer. Several types of slit were tried with the result that only a longitudinal one provided consistent results. In order to provide good control of melting it was necessary to use a thermocouple rather

than a pyrometer because with pyrometer control there was a surge in temperature on melting due to the change in emissivity. It was necessary to finely adjust the peak temperature so that a 10 mm molten zone was produced and then compress the sample while molten and during solidification to avoid porosity prior to tensile testing. The sample was then cooled at a constant rate. Tensile testing was conducted over a range of temperatures (650-1400°C) at a strain rate of $5s^{-1}$ which is much higher than the bending strain rate in continuous casting which is of the order of 10^{-3} to $10^{-2}s^{-1}$ for slab casters. A higher strain-rate was used so that the heating current could be switched off the instant the sample was pulled to avoid arcing across the two surfaces on fracture. A slower strain-rate test will require a knowledge of the time to fracture so that the heat can be switched off at the appropriate moment without causing too great a drop in temperature. This can be achieved by conducting a preliminary test for each condition.

The program used in the tests on mild steel is given in Table 1; the mechanical column indicates the stroke position, in this case starting at 1.00 cm and decreasing to 0.95 cm during solidification. The results of tensile testing are presented in Fig. 6. It can be seen that they follow the general form of the curve in Fig. 3 but with greater ductility in the temperature range 800 to 1000°C. The necking at fracture is shown in Fig. 7 for four samples tested at 650, 840, 1220 and 1395°C. Scanning electron microscopy was performed on the fracture surfaces and micrographs showing the various modes of fracture are presented in Figs. 8 and 9. At a temperature close to melting the sample failed intergranularly with evidence that this was from grain boundary melting (see Fig. 8(b)). At lower temperatures (1200-1300°C) the ductility is restored so that the reduction in area was almost 100%. Decreasing the temperature still further resulted in a drop in ductility; an example of a fracture in this region is given in Fig. 9. It is not possible to offer an explanation of the ductility trough between 800°C and 1000°C based on this investigation. However previous work on similar material has shown that the precipitation of sulphides plays an important role.

The results of this study indicate that a procedure involving melting, solidification and hot tensile testing can be performed successfully and can now be applied in the simulation of continuous casting of materials that have shown a tendency to cracking.

HOT ROLLING

As mentioned previously the use of the Gleeble, which can only provide uniaxial loading, as a means of simulating hot rolling is limited, because in tension necking will occur relatively early during straining and in compression barreling and friction will only allow a limited strain to be imposed.

An evaluation of the feasibility of employing the Gleeble to simulate hot rolling will begin shortly. A dilatometer will be used to control the reduction in area for tests in tension at various stages of a typical thermal cycle found in a rolling mill. The prospect of also using compression will be examined.

CONCLUSIONS

Simulation of the weld heat affected zone using the Gleeble is well established and has provided data which when combined with results from real welds enables an evaluation and improvement of the structure and properties of the heat affected zone to be carried out.

A procedure involving melting, solidification and subsequent tensile testing at high temperature has been successfully developed using the Gleeble with the aim of understanding the tendency to cracking of certain steels during continuous casting.

FUTURE WORK

The following list contains the specific tasks that will be carried out in future work on this project.

1. Compare the austenite grain size of real and simulated heat affected zones for a range of peak temperatures.
2. Measure the temperature distribution that exists on the surface of a Gleeble sample at a given grip separation distance and determine the temperature gradient between surface and centre.
3. Carry out a simulation of continuous casting on steels supplied by Algoma and Stelco.
4. Set up a procedure to simulate hot rolling.

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Table 1 - Program to provide controlled melting and solidification

Time(s)	Temp(°c)	Mechanical (cm)	Control switches
10.00	0	1.00	1,2,3
60.00	1350	1.00	0,1,2,3,6,10
10.00	1435	1.00	0,1,2,3,6,10
40.00	1435	1.00	0,1,2,3,6,10
10.00	1390	0.95	0,1,2,3,6,10
10.00	T	0.95	0,1,2,3,6,10
20.00	T	0.95	0,1,2,3,6,10
10.00	0	5.95	0,1,3,6,10

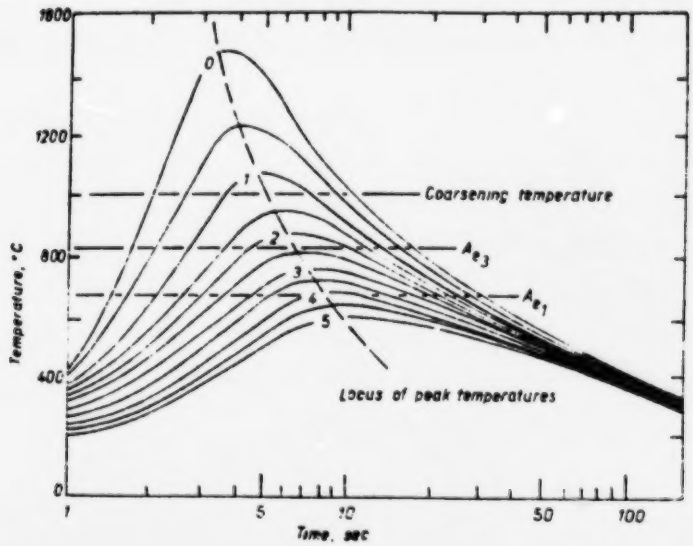

Fig. 1. Typical tehrmal cycles near an arc weld made with 2.75 kJ/mm heat input in 12 mm steel plate. The numbers on the curves indicate the elapsed time in seconds. (neg 8243)

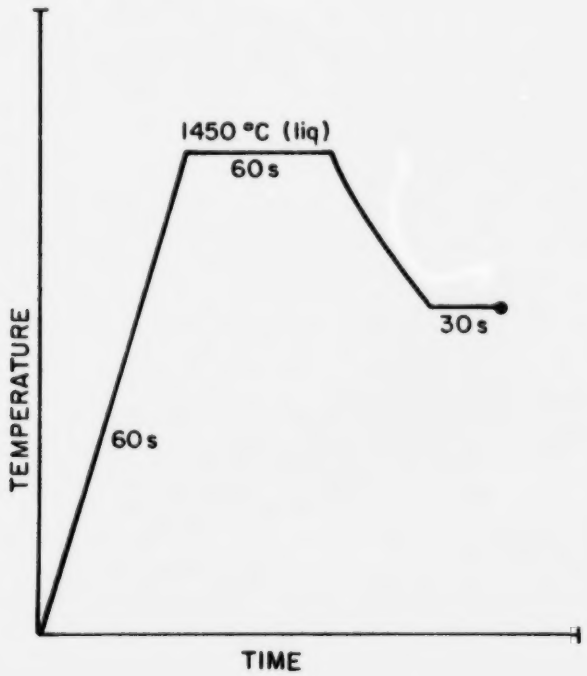

Fig. 2. Thermal profile for in situ melting and solidification. Suzuki et al (17). (neg 8244)

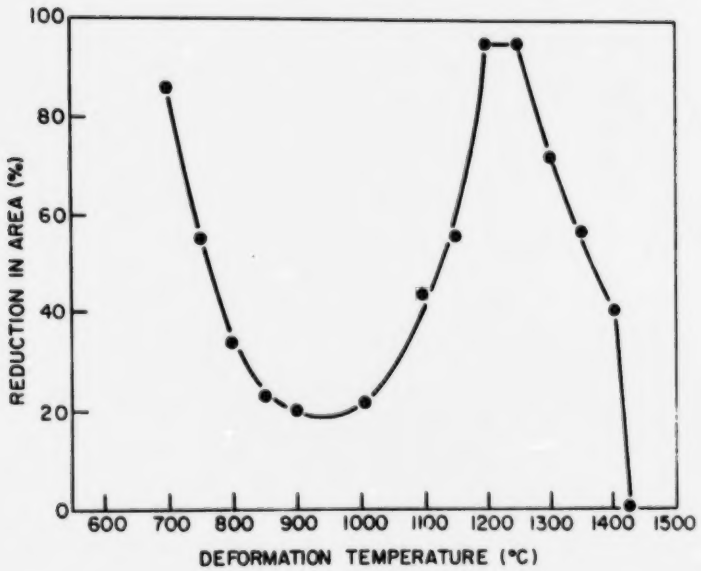

Fig. 3. Hot ductility curve for a plain C steel (0.12C, 0.35 mn, 0.01 Si, 0.014 P, 0.012S) following melting and solidification. Suxuki et al (17). (neg 8248)

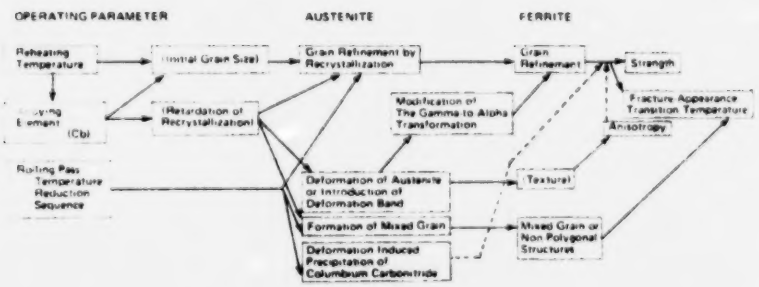

Fig. 4. Inter-relationship of factors involved in rolling. (neg 8246)

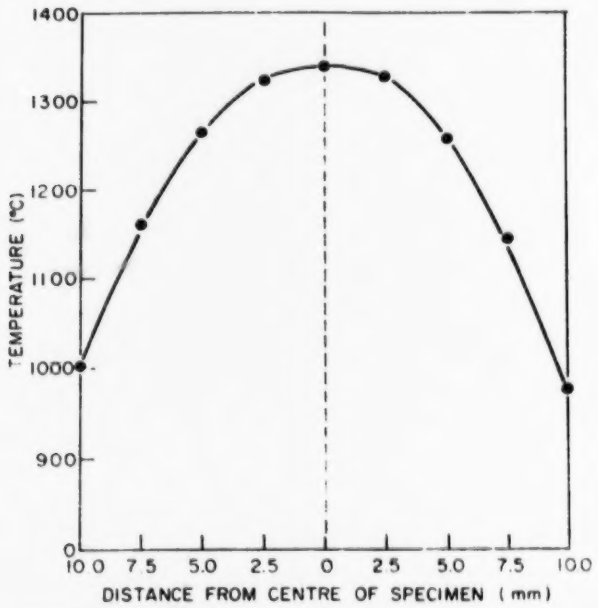

Fig. 5. Thermal profile along the length in the middle of a face of a Gleeble bar. Peak temperature 1350°C, Grip Separation 30 mm. (neg 8245)

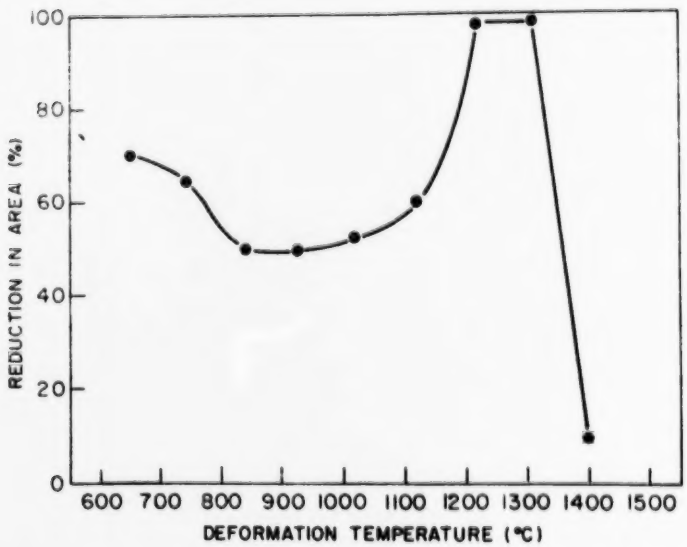

Fig. 6. Hot ductility curve for mild steel following melting and solidification in Gleeble. (neg 8247)

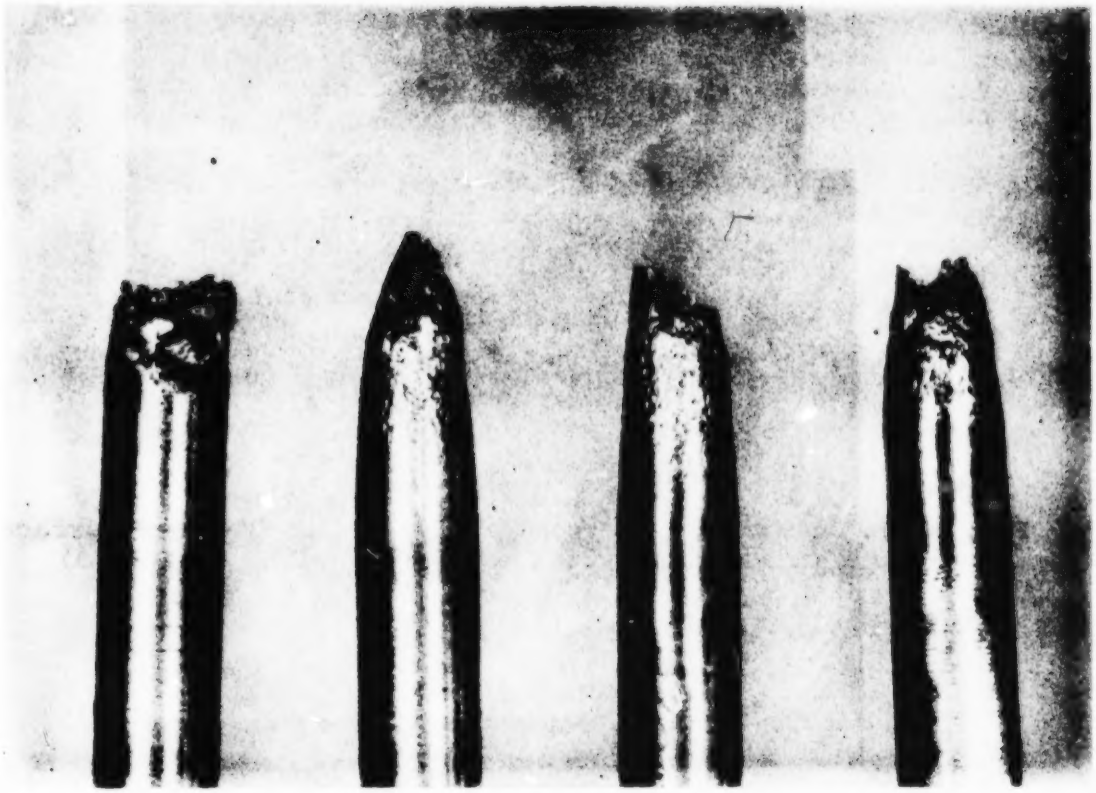

Fig. 7. Mild steel bar fractured at various temperatures following melting and solidification. (neg 8242)

Fig. 8(a). Scanning electron micrograph of fracture surface following testing at 1395°C x 85. (neg 8973)

Fig. 8(b). Scanning electron micrograph of one of the above grain boundary facets showing the presence of MnS x 550. (neg 8973)

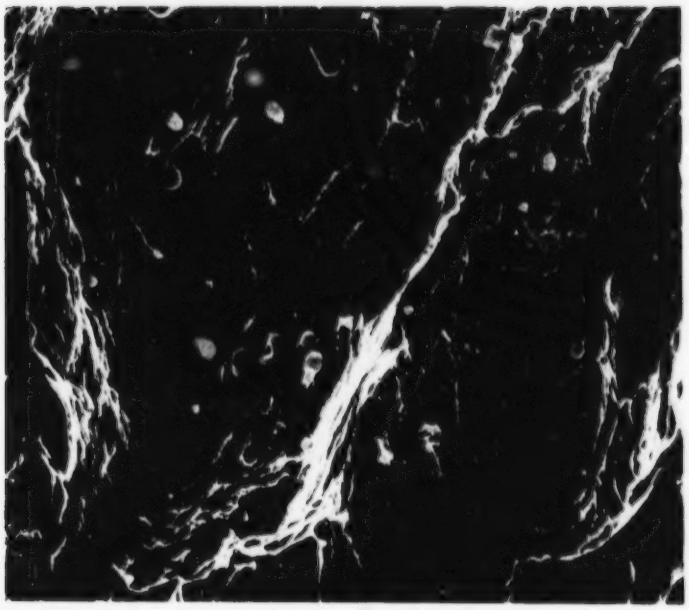

Fig. 9. Scanning electron micrograph of fracture surface following testing at 840°C x 1300. (neg 8973)